Development of Automated Whistle and Click Classifiers for Odontocete Species in the Western Atlantic Ocean and the Waters Surrounding the Hawaiian Islands

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LONG-TERM GOALS

1. Create combined whistle and click classifiers for odontocetes in the northwest Atlantic Ocean, the temperate Pacific Ocean and the waters surrounding the Hawaiian Islands. These classifiers will also incorporate ancillary information about acoustic encounters.
2. Examine geographic variation in the characteristics of whistles and clicks produced by species that are found in two or more of the three areas included in this effort.

OBJECTIVES

The primary objective of this effort is to develop combined automated whistle and echolocation click classifiers for odontocete species in the northwest Atlantic Ocean, the waters surrounding the Hawaiian Islands and the temperate Pacific Ocean. We will also incorporate ancillary information (e.g., vocalization rate, relative abundance of whistles and clicks, latitude of acoustic encounter) about acoustic encounters into the classifiers in an effort to improve the accuracy of classification results. These classifiers will be implemented in an existing whistle classifier, known as the Real-time Odontocete Call Classification Algorithm (ROCCA). ROCCA currently is available to users as a module in the acoustic processing software platform PAMGuard (Gillespie et al. 2008). Additionally, we will examine geographic variation in the characteristics of whistles and clicks produced by species that are found in two or more of the three areas included in this effort. These comparisons will provide important information about the necessity of creating different classifiers for different geographic areas.

APPROACH

Task 1: Automated collection of ancillary feature vectors

Ancillary variables such as the relative number of clicks and whistles present in an acoustic encounter and the click and/or whistle rate can be calculated based on the output of the automated detectors. We will create 'ancillary information' feature vectors based on automated detector output.

Task 2: Train and test classifiers

Three different feature vectors will be created using variables measured from clicks, whistles and ancillary information related to the acoustic encounter. Click variables will be measured automatically by ROCCA using information passed from PAMGuard's automated click detector. Implementation of the ROCCA click measurement modules was completed during a related LMR funded effort. The whistle feature vector will include 56 variables that are measured automatically by ROCCA (see Oswald 2013 for a description of these variables). The variables will be measured using the output of PAMGuard's automated tonal detector. The automated detector will pass time-frequency contours to ROCCA, and ROCCA will automatically measure features from the contours.

For this task, feature vectors will be created using visually validated, single species acoustic recordings collected in the northwest Atlantic Ocean, the temperate Pacific Ocean and the waters surrounding the Hawaiian Islands. Data have been provided by the Southeast Fisheries Science Center (SEFSC), the Northeast Fisheries Science Center (NEFSC), the Pacific Islands Fisheries Science Center (PIFSC), Woods Hole Oceanographic Institution (WHOI) and Duke University.

Three random forest classifiers will be trained for each study area: one for whistles, one for clicks and one for ancillary information pertaining to the acoustic encounters. Once three individual classifiers have been trained and tested, a second step will be implemented where the output of the three classifiers are combined and evaluated to determine a final classification for each odontocete encounter.

Task 3: Geographic comparison of whistles and clicks

We will include species that occur in multiple study areas in the geographic comparison. Species will be chosen based on sample size and occurrence in the study areas. Features measured from whistles and echolocation clicks recorded in the northwest Atlantic Ocean, Hawaii, and the temperate Pacific Ocean will be compared using statistics such as Kruskal-Wallis tests and Dunn's tests. This task will be completed after measurement of whistles and echolocation clicks from all three locations, but before training classifiers for these regions. If significant differences are not found among locations, this will allow us to include whistles and/or echolocation clicks from multiple locations in a single classifier.

WORK COMPLETED

Task 1: Automate collection of 'ancillary' variables

- Java code has been written to calculate ancillary variables using the output of the automated whistle and click detectors. These ancillary variables include: minimum, maximum and average time between whistles, minimum, maximum and average time between clicks, number of whistles/second, number of clicks/second, whistle 'density' (sum of whistle durations/duration of encounter), click density (sum of click durations/duration of encounter), whistle overlap (total number of seconds during which whistles overlap/duration of encounter), whistle duration (time between the start of the first whistle and the end of the last whistle), click duration (time between the start of the first click and the end of the last click), number of whistles, number of clicks
- Ancillary variable code has been added to the ROCCA module in PAMGuard

Task 2: Creation of feature vectors

- We have measured whistles, clicks and ancillary variables from all Atlantic data available to us (**Table 1**). Because of restrictions on the use of the SEFSC data, we are permitted use those recordings only for the whistle and ancillary feature vectors, as such separate columns for whistles and clicks are provided in **Table 1**.
- We have measured whistles, clicks and ancillary variables from 225 out of 287 encounters from the Hawaii data available to us (**Table 2**)
- We have measured whistles, clicks and ancillary variables from 107 out of 115 encounters from the temperate Pacific data available to us (**Table 3**). An additional 103 encounters were received from SWFSC and have been analyzed to obtain whistle measurements (**Table 3**, column 3). Click measures from this dataset have been made by SWFSC using the same methods as we used here and will be obtained from them during the first quarter of FY16.

Table 1. Number of northwest Atlantic encounters containing whistles and/or clicks. All encounters have been processed to obtain measurements.

Species	Number of whistle encounters	Number of click encounters
Atlantic spotted dolphin	55	35
Bottlenose dolphin	109	47
Clymene dolphins	4	0
Short-beaked common dolphin	11	7
False killer whale	2	0
Pantropical spotted dolphin	2	0
Short-finned pilot whale	17	16
Risso's dolphin	11	0
Rough-toothed dolphin	5	2
Striped dolphin	14	4
Grand Total	**232**	**120**

Table 2. Number of Hawaii encounters containing whistles and/or clicks. Number of encounters that have been processed to obtain measurements is given in parentheses.

Species	**Number of acoustic encounters**
Bottlenose dolphin	52 (52)
Cuvier's beaked whale	7 (7)
False killer whale	26 (12)
Fraser's dolphin	2 (0)
Melon-headed whale	35 (27)
Pilot whale	42 (42)
Pygmy killer whale	6 (6)
Risso's dolphin	7 (7)
Rough-toothed dolphin	25 (13)
Sperm whale	15 (0)
Spinner dolphin	19 (17)
Spotted dolphin	26 (17)
Striped dolphin	25 (25)
Tropical bottlenose whale	1 (0)
Grand Total	**287 (225)**

Table 3. Number of temperate Pacific encounters containing whistles and/or clicks. Number of encounters that have been processed to obtain measurements is given in parentheses.

Species	**Number of acoustic encounters**	**Additional encounters analyzed**
Baird's beaked whale	6 (6)	2
Bottlenose dolphin	9 (9)	14
Cuvier's beaked whale	8 (8)	0
Dall's porpoise	1 (0)	0
Killer whale	1 (1)	6
Long-beaked common dolphin	12 (12)	9
Northern right whale dolphin	4 (4)	0
Pacific white-sided dolphin	4 (4)	0
Risso's dolphin	13 (13)	9
Short-beaked common dolphin	45 (41)	54
Sperm whale	4 (2)	0
Striped dolphin	7 (7)	9
Grand Total	**115 (107)**	**103**

Task 3: Geographic comparison of whistles and clicks

- Whistles recorded from bottlenose dolphins, striped dolphins, pilot whales and short-beaked common dolphins in the tropical Pacific, northwest Atlantic and temperate Pacific study areas have been measured manually and automatically and compared.

- Echolocation clicks recorded from bottlenose dolphins, common dolphins, striped dolphins, pilot whales, and Cuvier's beaked whales recorded in the Hawaii, northwest Atlantic and temperate Pacific study areas have been measured automatically and compared.

RESULTS

Echolocation click measurements

Review of the click measurements from the northwest Atlantic dataset (**Figure 1)** suggests that echolocation measures will be useful for deveolping species classifiers. Non-parametric Kruskal-Wallis and post-hoc Dunn's tests with Bonferroni adjustment were used to compare echolocation click parameters among species and a number of significant differences are evident (**Table 4**).

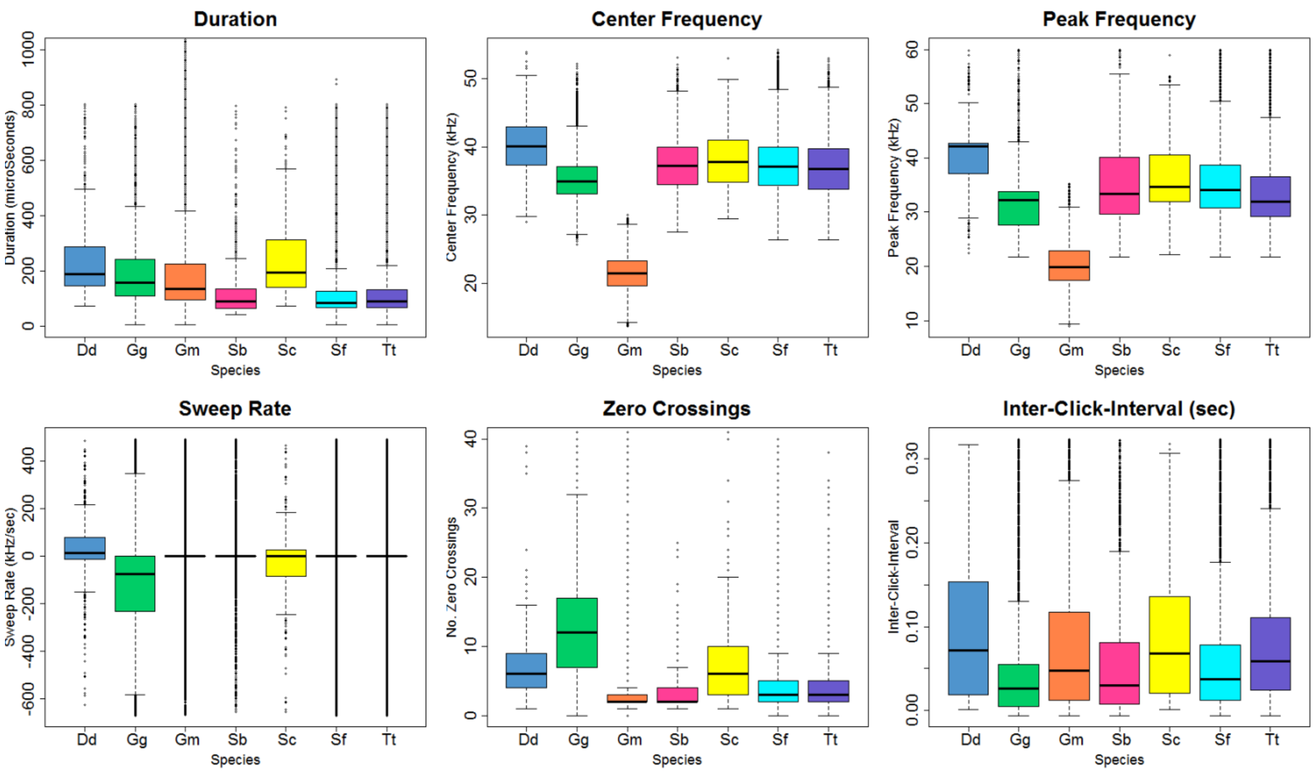

Figure 1. Box plots displaying the median, first and third quartiles for each echolocation click parameter measured from the northwest Atlantic dataset, with species along the x-axis and each parameter along the y-axis. The inter-click interval measures are measured automatically and not by individual click train, and thus are not an accurate representation for each species due to multiple individuals clicking simultaneously in many cases (Dd = short beaked common dolphin; Gm = short finned pilot whale; Sc = striped dolphin; Tt = bottlenose dolphin and Zc = Cuvier's beaked whale).

Table 4. Matrix displaying echolocation click parameters that were significantly different when compared among species (Kruskall-Wallis test and Dunn's tests with Bonferoni adjustment, α = 0.05).

	Common Dolphin	Risso's Dolphin	Pilot Whale	Rough-toothed Dolphin	Striped Dolphin	Atlantic Spotted Dolphin
Risso's Dolphin	All Parameters Significant					
Pilot Whale	All Parameters Significant	All Parameters Significant				
Rough-toothed Dolphin	All Parameters Significant	All Parameters Significant	Duration Center Frequency Peak Frequency Inter-Click Interval			
Striped Dolphin	Center Frequency Peak Frequency Sweep Rate	All Parameters Significant	Duration Center Frequency Peak Frequency Zero Crossings Inter-Click Interval	Duration Peak Frequency Zero Crossings Inter-Click Interval		
Atlantic Spotted Dolphin	All Parameters Significant	All Parameters Significant	Duration Peak Frequency Center Frequency Zero Crossings Inter-Click Interval	Duration Peak Frequency Zero Crossings Inter-Click Interval	Duration Zero Crossings Inter-Click Interval	
Bottlenose Dolphin	All Parameters Significant	All Parameters Significant	All Parameters Significant	All Parameters Significant	Duration Center Frequency Peak Frequency Zero Crossings Inter-Click Interval	All Parameters Significant

In order to further explore the utility of click measurements for species classification, a Discriminant Function Analysis (DFA) was used to classify species (**Table 5**). Pilot whales, Risso's dolphins, common dolphins, and bottlenose dolphins all had high correct classification scores compared to 14% correct classification expected by chance alone. Results suggest that clicks can be used for classification of at least some species. Combining information from clicks with other information such as whistle measurements and recording context has the potential to increase classification success.

Table 5. Classification matrix for DFA (with equal prior probability distribution; variables used: peak frequency, center frequency, duration, sweep rate and number of zero crossings) showing the percentage of clicks classified as each species with the correct classification score by species highlighted yellow.

	Common Dolphin	Risso's Dolphin	Pilot Whale	Rough-toothed Dolphin	Striped Dolphin	Atlantic Spotted Dolphin	Bottlenose Dolphin
Common Dolphin	67%	6%	0%	2%	7%	6%	11%
Risso's Dolphin	2%	68%	0%	2%	7%	3%	16%
Pilot Whale	0%	0%	100%	0%	0%	0%	0%
Rough-toothed Dolphin	22%	0%	1%	16%	2%	14%	44%
Striped Dolphin	28%	14%	0%	10%	16%	12%	20%
Atlantic Spotted Dolphin	19%	5%	0%	13%	4%	22%	36%
Bottlenose Dolphin	16%	6%	1%	11%	5%	12%	48%

Geographic comparison of whistles

Training and testing classifiers requires visually validated, single species recordings and large amounts of data, which can be difficult to obtain. Combining data recorded in different locations to train classifiers would allow for larger sample sizes, however, significant geographic variation in whistle structure is known to occur for several species of odontocetes, including bottlenose dolphins (May-Collado and Wartzok 2008), short-beaked common dolphins (Ansmann et al. 2007), spinner dolphins (Bazua-Duran and Au 2004) and Atlantic spotted dolphins (Baron et al. 2008). The fact that whistle structure varies both within and between ocean basins suggests that classification algorithms will be most effective when created specifically for locations and populations for which they will be used. To

test this hypothesis, we performed statistical comparisons of features measured from clicks and whistles produced by the same species in multiple geographic locations.

Automatically measured whistles

Kruskal-Wallis and Dunn's tests with Bonferroni adjustment were used to compare 19 whistle variables among locations for short-finned pilot whales, striped dolphins, bottlenose dolphins and striped dolphins (**Tables 6 and 7**). Almost every comparison was significantly different. Whistle measurements were made automatically from whistle contours that were automatically detected and extracted using PAMGuard's whistle and moan detector. As a result, the data include false positives, fragmented whistle contours and inaccurate extractions. We are currently investigating methods for removing ('pruning') at least some of these inaccuracies from the data. When pruning methods have been determined and applied, the results of these geographic comparisons may change. Currently, our results support the hypothesis that classifiers should be trained using data collected in the location where they will be used. We will evaluate and compare the results of classifying whistles using a classifier trained with whistles from the same location and from different locations in order to further test this hypothesis.

*Table 6. Descriptive statistics for frequency variables measured from automatically extracted whistle contours. All variables reported in kHz. First quarter, half and third quarter are frequencies at one quarter, half and three quarters of the duration. P-values calculated using Kruskal-Wallis tests. Post-hoc pairwise comparisons calculated using Dunn's test with Bonferroni adjustment for species that occurred in more than two study areas. ** indicates a p-value <0.0001. Significant differences are denoted in red. TP = temperate Pacific.*

Species	Region	N	Measure	Maximum	Minimum	Beginning	Ending	Mean	Median	First Quarter	Half	Third Quarter
Short-finned pilot whale	Northwest Atlantic	25697	Median	11.25	7.97	9.56	9.47	9.71	9.75	9.75	9.75	9.66
			10th Percentile	4.18	2.25	3.19	2.63	3.36	3.38	3.38	3.38	3.09
			90th Percentile	21.94	17.44	20.01	19.22	19.61	19.69	19.88	19.69	19.50
	Hawaii	95685	Median	10.99	9.38	9.90	10.50	10.18	10.22	10.03	10.20	10.25
			10th Percentile	3.66	2.81	3.17	3.17	3.25	3.17	3.19	3.17	3.17
			90th Percentile	27.10	25.31	25.88	26.61	26.18	26.13	26.06	26.12	26.37
	Kruskal-Wallis		p	0.45	**	**	**	**	**	**	**	**
Striped dolphin	Northwest Atlantic	2595	Median	13.31	8.81	10.69	11.44	10.82	10.69	10.41	10.69	10.88
			10th Percentile	8.81	5.81	6.75	7.00	7.55	7.44	6.94	7.22	7.31
			90th Percentile	19.69	15.00	17.44	18.00	17.26	17.25	17.25	17.31	17.63
	Hawaii	48836	Median	15.63	12.70	13.67	14.63	14.10	14.16	13.92	14.16	14.26
			10th Percentile	9.38	7.69	8.06	8.72	8.60	8.54	8.35	8.54	8.69
			90th Percentile	31.01	27.83	28.81	29.79	29.39	29.30	29.10	29.30	29.54
	Temperate Pacific	10146	Median	12.94	11.34	11.72	12.38	12.05	12.05	11.91	12.09	12.19
			10th Percentile	9.19	7.97	8.25	8.81	8.66	8.63	8.53	8.63	8.72
			90th Percentile	17.81	16.41	16.84	17.34	17.05	17.06	17.06	17.12	17.25
	Atlantic-Hawaii		**	**	**	**	**	**	**	**	**	**

	pairwise											
	Atlantic - TP pairwise		**	**	**	**	**	**	**	**	**	**
	Hawaii - TP pairwise		**	**	**	**0.0011**	0.327	0.2986	**0.001**	**	**	**
	Kruskal-Wallis		p	**	**	**	**	**	**	**	**	**
Bottlenose dolphin	Northwest Atlantic	86857	Median	30.47	29.91	30.09	30.19	30.18	30.19	30.19	30.19	30.19
			10th Percentile	11.06	8.16	9.56	9.28	9.62	9.52	9.47	9.38	9.38
			90th Percentile	45.28	45.19	45.19	45.28	45.28	45.28	45.28	45.28	45.28
	Hawaii	64402	Median	15.19	11.91	13.22	13.69	13.51	13.50	13.41	13.50	13.67
			10th Percentile	9.18	6.84	7.57	7.88	8.00	7.88	7.69	7.81	7.88
			90th Percentile	25.59	23.63	24.28	24.66	24.31	24.32	24.32	24.38	24.41
	Temperate Pacific	13328	Median	15.19	12.47	13.69	13.88	13.74	13.78	13.78	13.88	13.88
			10th Percentile	9.19	7.03	7.78	7.88	8.29	8.25	8.06	8.22	8.06
			90th Percentile	31.69	28.69	30.00	30.28	30.11	30.19	30.19	30.19	30.38
	Atlanti-Hawaii pairwise		**	**	**	**	**	**	**	**	**	**
	Atlantic - TP pairwise		**	**	**	**	**	**	**	**	**	**
	Hawaii - TP pairwise		**	**	**	**	**	**	**	**	**	**
	Kruskal-Wallis		p	**	**	**	**	**	**	**	**	**
Short-beaked common dolphin	Northwest Atlantic	1830	Median	16.13	10.13	12.38	13.88	12.46	12.19	12.19	12.23	12.94
			10th Percentile	11.25	6.56	8.25	8.44	9.02	8.72	8.44	8.44	8.56
			90th Percentile	33.94	25.33	28.89	29.83	29.36	29.25	28.71	29.25	29.44
	Temperate Pacific	236158	Median	16.03	14.06	14.81	15.23	14.96	14.94	14.88	15.00	15.07
			10th Percentile	9.84	8.40	8.91	9.19	9.14	9.09	9.00	9.08	9.14

			90th Percentile	29.63	27.47	28.32	28.81	28.49	28.48	28.36	28.48	28.59
	Kruskal-Wallis		p	**	**	**0.03**	0.63	**	**	**	**	**

*Table 7. Descriptive statistics for shape variables measured from automatically extracted whistle contours. % up, down and flat are the percentage of the whistle contours with positive, negative and zero slope, respectively. P-values calculated using Kruskal-Wallis tests. Post-hoc pairwise comparisons calculated using Dunn's test with Bonferroni adjustment for species that occurred in more than two study areas. ** indicates a p-value <0.0001. Significant differences are denoted in red.*

Species	Region	N	Measure	Duration	Mean slope	Mean absolute slope	Mean positive slope	Mean negative slope	% up	% down	% flat	# steps	# inflect points
Short-finned pilot whale	Northwest Atlantic	25,697	Median	0.23	-13.58	175.56	70.31	-62.50	34.34	38.10	23.05	0	3
			10th Percentile	0.12	-169.64	58.18	18.75	-133.52	16.36	21.74	6.82	0	0
			90th Percentile	0.54	201.27	595.06	139.13	-18.66	61.11	71.20	30.41	3	9
	Hawaii	95,685	Median	0.10	19.76	142.03	42.48	-33.20	37.21	34.43	25.33	0	2
			10th Percentile	0.05	-113.55	43.21	8.17	-154.51	27.27	20.51	9.68	0	0
			90th Percentile	0.25	222.52	498.78	170.90	0.00	63.24	52.17	31.46	1	5
	Kruskal-Wallis		p	**	**	**	**	**	**	**	**	**	**
Striped dolphin	Northwest Atlantic	2,595	Median	0.28	18.07	229.77	81.75	-81.25	38.18	35.34	25.00	0	6
			10th Percentile	0.14	-113.22	65.52	16.32	-248.47	28.25	25.00	9.09	0	1
			90th Percentile	0.77	151.51	815.91	231.31	-12.39	55.83	51.02	30.05	7	18
	Hawaii	48,836	Median	0.12	51.79	295.33	122.07	-122.07	40.91	32.86	22.73	0	3
			10th Percentile	0.07	-183.10	8.07	18.93	-203.45	25.80	18.03	8.33	0	1
			90th Percentile	0.28	354.39	85.59	205.49	-17.61	68.24	54.84	29.87	0	9
	Temperate	10,146	Median	0.15	31.25	10.14	23.21	-19.49	44.07	32.08	19.6	0	2

	Pacific										7		
			10th Percentile	0.10	-69.08	4.35	17.19	-41.67	23.66	12.90	6.42	0	1
			90th Percentile	0.32	135.41	20.62	39.72	0.00	76.47	57.89	28.40	0	5
	Atlantic-Hawaii pairwise		**	**	**	**0.0007**	**	0.1657	**	**	**	**	**
	Atlantic - TP pairwise		**	**	**	**	**	**	**	**	**	**	**
	Hawaii - TP pairwise		**	**	**	**	**	**	**	**	**	**	**0.0439**
	Kruskal-Wallis		P	**	**	**	**	**	**	**	**	**	**
Bottlenose dolphin	Northwest Atlantic	86,857	Median	0.15	5.58	7.44	21.09	-18.75	34.83	34.88	24.24	0	2
			10th Percentile	0.11	-86.64	0.60	0.00	-56.25	23.53	27.14	6.92	0	0
			90th Percentile	0.32	80.00	29.90	58.59	0.00	56.52	60.00	32.95	0	7
	Hawaii	64,402	Median	0.18	21.02	16.15	29.90	-27.49	41.67	35.48	15.56	0	2
			10th Percentile	0.13	-144.95	6.68	17.81	-127.88	16.00	10.00	3.57	0	1
			90th Percentile	0.36	197.91	46.75	132.24	-15.63	82.76	72.41	27.34	0	7
	Temperate Pacific	13,328	Median	0.13	16.45	23.16	69.44	-62.50	37.68	36.07	20.00	0	2
			10th Percentile	0.04	-236.71	7.50	17.71	-121.53	16.00	13.51	3.30	0	0
			90th Percentile	0.33	331.95	76.33	125.00	-15.63	76.68	72.09	29.41	0	6
	Atlantic - Hawaii pairwise		**	**	**	**	**	**	**	**0.0002**	**	**	**
	Atlantic - TP pairwise		**	**	**	**	**	**	**	**	**	**	**
	Hawaii - TP pairwise		**	**	**	**	**	**	**	**0.0282**	**	**	**

	Kruskal-Wallis		p	**	**	**	**	**	**	**	**	**	**
Short-beaked common dolphin	Northwest Atlantic	1,830	Median	0.33	32.88	33.94	99.35	-103.57	39.40	34.43	25.31	0	8
			10th Percentile	0.20	-154.87	11.51	62.50	-269.59	28.79	25.74	13.92	0	3
			90th Percentile	1.00	224.87	106.21	253.96	-62.50	54.96	47.66	29.72	8	22
	Temperate Pacific	23,6158	Median	0.11	29.29	17.13	34.76	-32.45	40.54	33.33	20.00	0	2
			10th Percentile	0.04	-161.66	6.58	18.75	-101.73	18.68	13.64	4.55	0	0
			90th Percentile	0.28	214.06	45.09	106.35	0.00	76.00	67.39	29.17	0	5
	Kruskal-Wallis		p	**	0.42	**	**	**	**0.01**	0.16	**	**	**

Manually measured whistles
Automated datasets will contain false positive detections, fragmented whistles and deviations from actual whistle contours. Because of this, comparisons were made using a whistle dataset comprised of measurements taken from whistle contours that were traced using ROCCA's manual methods. This allowed us to examine geographic variation in the whistles without the confounding factors introduced by automated detection.

To increase sample size for the manual whistle analysis, the Hawaii study area was expanded to include the tropical Pacific Ocean between Hawaii and south/central America. This allowed us to compare whistles of four species recorded in both the tropical Pacific and the northwest Atlantic (striped dolphins, short-beaked common dolphins, bottlenose dolphins and short-finned pilot whales).

Kruskal-Wallis tests were used to compare 20 whistle variables between locations for all four species (**Tables 8 and 9**). Many significant differences were found in frequency variables for short-finned pilot whales and striped dolphins and no significant differences were found in frequency variables for bottlenose dolphins (**Table 8**). Approximately half of the shape variables were significantly different between study areas for every species (**Table 9**). The large number of variables that were significantly different between study areas suggests that classifiers should be trained and tested using only whistles recorded in the location where the classifiers will be used.

In addition to comparisons of whistle features, we also examined the effects of geographic variation on classifier performance. In this analysis, a random forest classifier trained using whistles recorded in the tropical Pacific was used to classify whistles recorded in the northwest Atlantic, and vice versa. These results were compared to the results of classifiers trained and tested using only tropical Pacific or northwest Atlantic whistles. This analysis was performed using manually extracted whistle contours. The same analyses for automatically extracted whistles and clicks are in progress and expected to be complete before the end of the calendar year.

For whistles recorded in the northwest Atlantic, correct classification scores were significantly higher (Fisher's exact test, $\alpha = 0.05$) when the classifier was trained using northwest Atlantic whistles versus when the classifier was trained using tropical Pacific whistles for every species except for striped dolphins (**Table 10)**. For whistles recorded in the tropical Pacific, correct classification scores were significantly higher (Fisher's exact test, $\alpha = 0.05$) when the classifier was trained using tropical Pacific whistles only for bottlenose dolphins (**Table 11**). These results support the hypothesis that a classifier will perform best when trained using whistles recorded in the location where the classifier will be used.

*Table 8. Descriptive statistics for frequency variables measured from manually extracted whistle contours. All variables reported in kHz. First quarter, half and third quarter are frequencies at one quarter, half and three quarters of the duration. P-values calculated using Kruskal-Wallis tests. Significant differences are denoted in red, ** indicates a p-value <0.0001. N = 109 for the tropical Pacific for each species. N = 250 for the northwest Atlantic for all species.*

Species	Region	Measure	Maximum	Minimum	Beginning	Ending	Range	Mean	Median	First quarter	Half	Third quarter
Short-finned pilot whale	Atlantic	Median	7.97	4.31	5.81	6.00	2.30	6.35	6.19	6.19	6.38	6.38
		10th percentile	3.92	2.06	2.98	2.44	0.75	3.13	3.19	3.19	3.18	2.99
		90th percentile	13.33	8.54	10.33	11.66	7.13	10.35	10.33	10.88	10.74	11.45
	Tropical Pacific	Median	6.94	4.22	4.57	5.86	2.52	5.35	5.25	5.33	5.33	5.45
		10th percentile	4.13	2.46	2.63	3.55	0.75	3.62	3.53	3.04	3.49	3.20
		90th percentile	13.05	7.07	8.11	10.58	6.34	10.54	10.40	9.39	10.38	11.30
		p	**0.01**	0.99	**0.01**	0.67	0.36	**0.003**	**0.001**	**	**0.001**	0.07
Striped dolphin	Atlantic	Median	14.06	8.70	10.15	11.18	5.25	11.00	10.69	10.66	10.69	11.06
		10th percentile	10.12	6.38	7.12	7.58	1.40	8.76	8.44	8.06	8.29	8.25
		90th percentile	19.23	11.81	15.38	16.00	11.06	13.87	13.88	14.25	14.82	14.66
	Tropical Pacific	Median	15.19	8.69	11.07	12.00	6.27	11.70	11.54	10.78	11.81	12.00
		10th percentile	10.01	6.27	6.79	8.05	2.03	8.96	8.77	7.79	8.62	8.62
		90th percentile	20.48	12.00	17.33	16.54	10.73	14.40	14.30	15.91	14.86	14.95
		p	**	0.97	0.35	0.23	**0.009**	0.14	0.10	0.37	0.21	**0.04**

Bottlenose dolphin	**Atlantic**	Median	16.88	8.06	11.44	11.06	8.25	12.12	11.81	12.19	12.00	11.72
		10th percentile	11.98	5.63	6.56	6.19	3.56	8.77	8.44	8.44	8.25	7.31
		90th percentile	22.93	10.88	18.58	18.21	13.89	15.42	16.14	18.00	17.64	17.44
	Tropical Pacific	Median	16.90	8.26	10.43	10.43	7.33	12.75	11.95	11.84	11.66	11.70
		10th percentile	10.48	5.53	6.73	6.19	2.67	7.98	7.85	7.60	7.83	7.05
		90th percentile	22.45	12.05	21.08	17.79	14.23	16.61	16.13	18.07	17.54	17.06
		p	0.86	0.29	0.33	0.13	0.18	0.47	0.62	0.51	0.95	0.97
Short-beaked common dolphin	**Atlantic**	Median	13.88	9.38	11.53	11.67	4.59	11.41	11.48	11.44	11.67	11.77
		10th percentile	10.96	6.90	8.38	8.55	1.34	9.30	8.63	8.25	8.44	8.60
		90th percentile	18.53	11.83	16.54	16.46	9.22	14.00	13.69	13.89	14.44	14.81
	Tropical Pacific	Median	15.23	8.31	11.88	11.45	6.84	11.38	11.31	10.99	11.06	11.31
		10th percentile	9.62	5.87	6.64	7.43	2.06	7.98	7.93	7.36	7.32	7.61
		90th percentile	21.30	11.53	18.72	18.44	12.42	14.92	14.29	14.98	15.63	16.39
		p	**	**	0.75	0.74	**	0.96	0.54	0.09	0.13	0.29

Table 9. Descriptive statistics for shape variables measured from manually extracted whistle contours. % up, down and flat are the percentage of the whistle contours with positive, negative and zero slope, respectively. P-values calculated using Kruskal-Wallis tests. Significant differences are denoted in red. N = 109 for the tropical Pacific for each species. N = 250 for the northwest Atlantic for all species.

Species	Region	Measure	Duration	Mean slope	Mean absolute slope	Mean positive slope	Mean negative slope	% up	% down	% flat	# steps	# inflection points
Short-finned pilot whale	Atlantic	Median	0.43	0.84	12.03	78.13	-78.13	36.27	34.90	29.41	0	2
		10th percentile	0.15	-9.28	3.07	14.77	-104.18	31.35	29.40	14.73	0	0.9
		90th percentile	0.77	12.95	56.81	106.84	0.00	49.34	44.28	32.35	2	3.1
	Tropical Pacific	Median	0.47	2.37	10.14	16.79	-13.09	40.38	11.43	36.36	0	0
		10th percentile	0.17	-7.39	2.77	5.00	-53.04	0.00	0.00	0.00	0	0
		90th percentile	1.05	12.41	32.24	56.58	0.00	95.65	54.55	69.60	1	2
		p	0.53	0.10	0.67	**	**	0.47	**	0.47	**	**
Striped dolphin	Atlantic	Median	0.57	0.75	13.33	69.32	-62.50	38.07	35.04	25.81	0	2
		10th percentile	0.21	-8.95	5.55	5.97	-98.34	27.79	26.69	1.96	0	1
		90th percentile	1.10	12.05	28.15	93.75	0.00	62.23	60.89	30.88	2	4
	Tropical Pacific	Median	0.60	0.74	19.39	24.75	-30.80	42.86	33.30	13.60	0	1
		10th percentile	0.20	-12.07	7.99	9.67	-86.01	2.79	0.00	0.00	0	0
		90th percentile	1.10	16.98	39.21	63.14	-4.18	80.36	65.90	55.74	3	4
		p	0.97	0.97	**	**	0.10	0.16	0.51	**0.001**	**0.03**	**
Bottlenose dolphin	Atlantic	Median	0.61	0.34	30.18	83.75	-86.48	37.92	37.77	24.41	0	2
		10th percentile	0.21	-14.33	10.64	0.00	-137.13	29.49	29.59	12.61	0	0

		90th percentile	1.41	15.76	75.05	132.19	-69.09	48.41	49.10	30.29	1	5
	Tropical Pacific	Median	0.74	-1.04	16.41	22.34	-15.54	27.92	53.85	2.60	0	1
		10th percentile	0.22	-13.62	7.14	8.30	-44.11	2.10	8.03	0.00	0	0
		90th percentile	1.58	14.46	35.62	55.24	-4.63	87.11	93.49	29.44	3	5
		p	**0.04**	0.07	**	**	**	0.18	**	**	0.06	**0.002**
Short-beaked common dolphin	Atlantic	Median	0.70	0.15	10.09	14.70	-19.82	39.16	34.38	19.05	0	2
		10th percentile	0.21	-7.61	4.08	4.64	-93.88	27.33	15.41	1.84	0	1
		90th percentile	1.47	9.91	21.61	78.13	0.00	78.64	63.34	30.75	1	5
	Tropical Pacific	Median	0.64	-0.05	17.14	16.52	-21.43	50.00	39.79	5.74	1	1
		10th percentile	0.17	-13.73	8.70	5.38	-53.40	10.22	3.99	0.00	0	0
		90th percentile	1.24	15.25	37.46	42.22	-5.38	86.62	75.00	27.75	5	4
		p	0.38	0.96	**	0.49	0.68	**	**0.03**	**	**	**0.003**

Table 10. Confusion matrices for northwest Atlantic whistles. The percent of whistles correctly classified for each species is in bold, with standard deviations in parentheses. A) Classifier trained using northwest Atlantic whistles. B) Classifier trained using tropical Pacific whistles.

A)

	% classified as				
Actual Species	**Short-beaked common dolphin**	**Short-finned pilot whale**	**Striped dolphin**	**Bottlenose dolphin**	**n**
Short-beaked common dolphin	**45.9 (2.8)**	3.2 (0.87)	34.1 (4.5)	16.8 (2.7)	249
Short-finned pilot whale	3.1 (0.9)	**75.3 (1.7)**	13.3 (1.5)	82.5 (1.3)	249
Striped dolphin	33.8 (4.8)	7.2 (1.3)	**33.7 (5.8)**	25.3 (3.2)	249
Bottlenose dolphin	6.3 (1.6)	7.3 (1.4)	15.8 (2.3)	**70.4 (2.5)**	249

B)

	% classified as				
Actual Species	**Short-beaked common dolphin**	**Short-finned pilot whale**	**Striped dolphin**	**Bottlenose dolphin**	**n**
Short-beaked common dolphin	**23.5 (5.9)**	1.7 (0.49)	54.2 (6.4)	20.6 (5.6)	249
Short-finned pilot whale	1.9 (1.3)	**63.4 (1.4)**	32.4 (2.4)	2.3 (1.1)	256
Striped dolphin	12.6 (2.5)	3.6 (0.74)	**67.7 (2.7)**	16.2 (1.8)	365
Bottlenose dolphin	2.6 (1.7)	4.1 (0.29)	76.9 (5.9)	**16.4 (5.1)**	2982

Table 11. Confusion matrices for tropical Pacific whistles. The percent of whistles correctly classified for each species is in bold, with standard deviations in parentheses. A) Classifier trained using tropical Pacific whistles. B) Classifier trained using northwest Atlantic whistles.

A)

	% classified as				
Actual Species	**Short-beaked common dolphin**	**Short-finned pilot whale**	**Striped dolphin**	**Bottlenose dolphin**	**n**
Short-beaked common dolphin	**48.5 (5.7)**	5.6 (1.5)	23.1 (5.1)	22.9 (3.5)	109
Short-finned pilot whale	4.8 (1.9)	**80.1 (1.5)**	11.3 (2.2)	4.3 (1.8)	109
Striped dolphin	32.2 (3.8)	4.9 (1.9)	**49.1 (4.9)**	14.0 (2.9)	109

Bottlenose dolphin	23.1 (4.5)	5.9 (1.4)	17.3 (3.9)	**53.8 (4.8)**	109

B)

	% classified as				
Actual Species	**Short-beaked common dolphin**	**Short-finned pilot whale**	**Striped dolphin**	**Bottlenose dolphin**	**n**
Short-beaked common dolphin	**37.6 (2.9)**	6.5 (0.90)	55.3 (3.3)	0.61 (0.69)	226
Short-finned pilot whale	21.4 (0.8)	**83.0 (0.32)**	10.2 (1.3)	5.0 (0.90)	109
Striped dolphin	28.9 (2.4)	4.0 (0.41)	**55.8 (2.6)**	11.5 (1.4)	452
Bottlenose dolphin	27.3 (2.8)	6.7 (0.69)	63.6 (2.9)	**2.3 (0.65)**	155

Echolocation Clicks

Echolocation clicks were analyzed from bottlenose dolphins, common dolphins, pilot whales, striped dolphins and Cuvier's beaked whales and parameters were compared among regions. The total number of clicks measured by species and region is shown in **Table 12**.

Table 12. Number of echolocation clicks measured by species and region for geographic comparison

Species	Region			Total
	Atlantic	Hawaii	Temperate Pactific	
Bottlenose dolphin	38,592	251,733	61,223	351,548
Common dolphin	725	0	144,584	145,309
Pilot whale	23,460	96,622	0	120,082
Striped dolphin	324	62,215	206	62,745
Cuvier's beaked whale	0	1,828	77,117	78,945

Boxplots showing the click parameters used in this analysis are shown in **Figure 2**.

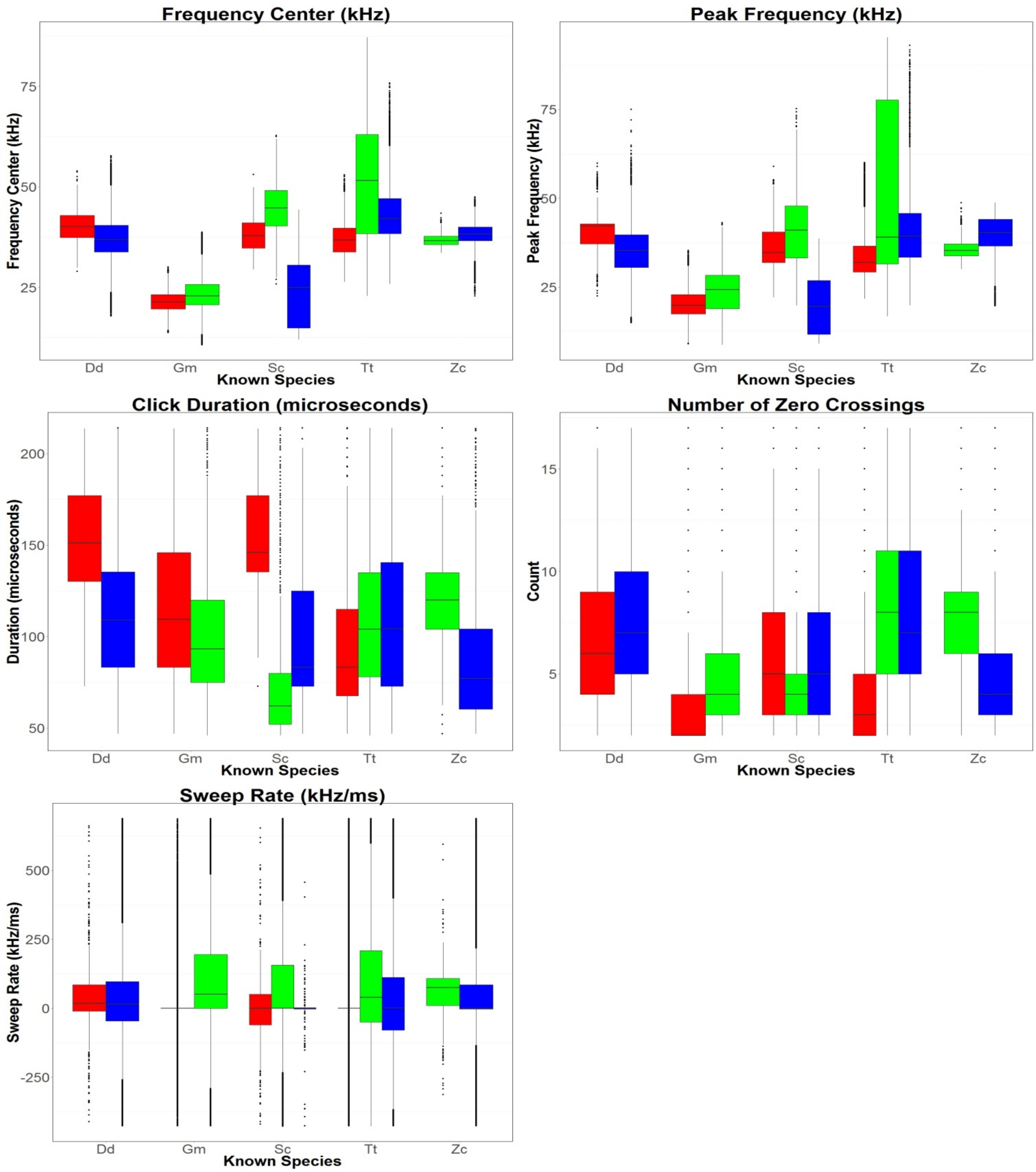

Figure 2. Box plots displaying the median, first and third quartiles for each echolocation click parameter used in the geographic comparison with species codes along the x-axis (Dd = short beaked common dolphin; Gm = short finned pilot whale; Sc = striped dolphin; Tt = bottlenose dolphin and Zc = Cuvier's beaked whale) and each parameter along the y-axis. Each species display shows a colored box for each geographic region (red = Atlantic; green = Hawaii and blue = Temperate Pacific).

Non-parametric Kruskal-Wallis and post-hoc Dunn's tests with Bonferroni adjustment were used to compare the five echolocation click parameters among regions by species. Significant differences in several click parameters were found for all species among the regions compared (**Table 13**). These results suggest that it is important to develop classifiers for each region independently.

Table 13. Matrix displaying echolocation click parameters by species that were significantly different when compared among locations (Dunn's test with Bonferroni adjustment $p < 0.05$).

	Atlantic	**Hawaii**
Temperate Pacific	Bottlenose dolphin: (dur, center freq, peak freq, NCrossings, sweep rate) Common dolphin: (center freq, peak freq, NCrossings, sweep rate) Pilot whale: **(No Data Available)** Striped dolphin: (dur, center freq, peak freq, sweep rate) Cuvier's beaked whale: **(No Data Available)**	Bottlenose dolphin: (dur, center freq, peak freq, NCrossings, Sweep Rate) Common dolphin: **(No Data Available)** Pilot whale: **(No Data Available)** Striped dolphin: (center freq, peak freq, sweep rate) Cuvier's beaked whale: (dur, center freq, peak freq, NCrossings)
Hawaii	Bottlenose dolphin: (dur, center freq, peak freq, NCrossings, sweep rate) Common dolphin: **(No Data Available)** Pilot whale: (dur, center freq, peak freq, NCrossings, sweep rate) Striped dolphin: (dur, center freq, peak freq, sweep rate) Cuvier's beaked whale: **(No Data Available)**	

IMPACT/APPLICATIONS

The three study areas included in this effort all include training areas that are frequently used by the U.S. Navy, therefore knowledge of when and how species are using these areas is particularly important. Passive acoustic monitoring (PAM) is now being used extensively to collect information regarding marine mammal occurrence, distribution and behavior in Naval exercise areas. The enormous volumes of data currently being generated during PAM projects require automated methods for efficient and timely processing. Also, the ability to automatically detect, measure and classify vocalizations in real-time reduces the need for highly skilled, costly personnel during at-sea operations and post-processing and thereby reduces operational costs. Combining whistle and click classifiers will allow the classification of a greater proportion of acoustic encounters with greater accuracy than is possible when relying on whistles alone. The ability to classify odontocete vocalizations to species with a high degree of confidence will allow the examination of distribution patterns and habitat use as well as the development of management and mitigation strategies on a species-by-species basis.

RELATED PROJECTS

This project is part of a larger effort funded jointly by LMR and ONR. The LMR-funded effort began in April, 2014. During this effort, we evaluated the performance of three automated tonal detection and extraction algorithms and the algorithm that produced the most accurate detections and contour extractions (PAMGuard's tonal detector) was used to detect and measure whistles in this ONR-funded effort. During the FY14 LMR-funded effort, we also integrated PAMGuard's automated click detector with ROCCA and added automated click measurement capabilities to ROCCA via PAMGuard software. These capabilities were used to measure clicks in this ONR-funded effort. In FY16, the LMR-funded effort will continue. During this time we will train and test temperate Pacific classifiers (using feature vectors created during ONR FY15) as well as integrate the automated detectors and classifiers into both PAMGuard and Ishmael software to make them easily accessible to end-users.

REFERENCES

Ansmann, I.C., J.C. Goold, P.G.H. Evans, M. Simmonds and G.K. Simon. 2007. Variation in the whistle characteristics of short-beaked common dolphins, *Delphinus delphis*, at two locations around the British Isles. *J. Mar. Biol. Assoc. U.K.* 87:19-26.

Baron, S.C., A. Martinez, L.P. Garrison, and E.O. Keith. 2008. Differences in acoustic signals from delphinids in the western North Atlantic and northern Gulf of Mexico. *Mar. Mamm. Sci.* 24:42-56.

Bazua-Duran, M.C. and W.W.L. Au. 2004. Geographic variations in the whistles of spinner dolphins (*Stenella longirostris*) of the main Hawaiian Islands. *J. Acoust. Soc. Am. 116:3757-3769.*

Gillespie, D.M., Gordon, J., McHugh, R., Mclaren, D., Mellinger, D., Redmond, P., Thode, A., Trinder, P. and Deng, X.Y. 2008. PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localisation of cetaceans. Proceedings of the Institute of Acoustics, 30 Pt 5. United Kingdom.

May-Collado, L.J., and D. Wartzok. 2008. A comparison of bottlenose dolphin whistles in the Atlantic Ocean: factors promoting whistle variation. *J. Mamm.* 89:1229-1240.

Oswald, J.N. 2013. *Development of a Classifier for the Acoustic Identification of Delphinid Species in the Northwest Atlantic Ocean. Final Report*. Submitted to HDR Environmental, Operations and Construction, Inc. Norfolk, Virginia under Contract No. CON005-4394-009, Subproject 164744, Task Order 003, Agreement # 105067. Prepared by Bio-Waves, Inc., Encinitas, California.